Normal Mode Properties and Signal Coherence in Shallow Water Propagation

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BACKGROUND

For many years, the 6.1 basic research communities have focused on the effects of internal waves on temporal coherence; whereas, Navy applied programs are more concerned with the randomizing effect of the combination of bottom bathymetry variations and platform motion on array (spatial) coherence. We find that it is not possible to isolate these two causes in the shallow ocean. In the deep ocean and for propagation by refracted paths, one need only consider the effects of internal waves to understand coherence. But in shallow oceans, propagation is generally by reflected paths and bottom variability can and does affect coherence and often is more randomizing that internal waves. We have found that for very low frequencies the bottom bathymetry variation are a small fraction of the acoustic wavelength and the bottom appears flat and internal waves alone determine coherence. At very high frequencies the bottom variations are a large fraction of the wavelength and so even the slightest sound speed variations randomize and de-correlate the signal even without internal waves. But for the practical mid-frequency range, (400Hz to 3kHz), the effects of each cause are interwoven and generally inseparable.

OBJECTIVES

Our objective has been to observe and model the coherence properties of individual mode arrivals. We find that understanding of mode properties holds promise of explaining and predicting both temporal and spatial coherence for fixed and moving platforms. The two distinct coherences, temporal and spatial, are related to the same mode properties. Stable clean modes result in temporal and spatial coherence but distorted and randomized modes result in loss of coherence - all predictable with physical models with appropriate random inputs for the medium and boundaries. Previous attempts by other investigators to model coherence using ray models were unsuccessful owing to chaos introduce by ray theory approximations.

METHODS

The research presented here is in its third stage. First, the data from three shallow water experiments were analyzed to observe and compare coherence properties of individual mode arrivals in both space and time. Mode coherence measures were systematically compared for different frequencies, mode numbers and channel parameters and for a variety of internal wave energy levels. A number of consistent trends and relation were observed. For example, lower order modes were more coherent than higher order modes especially at higher frequencies. Low frequency coherence is mostly determined by internal waves while high frequency coherence is limited by bathymetry fluctuations. And, both spatial and temporal coherence exhibit the same trends and relationships. Of note is the finding that the qualitative features of temporal and spatial coherence show the same dependence on frequency and mode number. This suggests the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2012**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Normal Mode Properties and Signal Coherence in Shallow Water Propagation**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Miami**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

possibility of a single unified theory to predict temporal and spatial coherence using statistics of the internal wave field and bathymetry as inputs. Our research is pursuing this avenue with very encouraging results so far.

The second effort concerns modeling. Two and three dimensional broadband PE models were developed with mode coherency computed from the output. With these models, mode coherency is the output when sound speed field and bathymetry variation statistics are inputs. Here the effort splits in two coordinated directions with each the topic of a dissertation. Filipe Lourenco, a Brazilian Naval officer studies the sound speed fluctuations and Ms. Jennifer Wylie combines the sound field statistics with bathymetry statistics. Once the models were developed and tested, the approach is straightforward. Statistics of the sound speed field and bottom are computed from the SHARK environmental arrays and geo surveys. Model outputs are used to compute mode coherence which is then compared mode coherence calculated for acoustics signals. Thus far the results are in remarkable close agreement with observations.

RESULTS

We have consistent measurements over 6 octaves of frequency from 3 experiments sites. For each transmission there are several hours and sometimes days from which temporal coherence of individual modes can be computed. For each transmission there are usually 4 to 10 identifiable surface-reflected-bottom-reflected mode arrivals. We look for consistent findings to investigate and understand with propagation models. There are several.

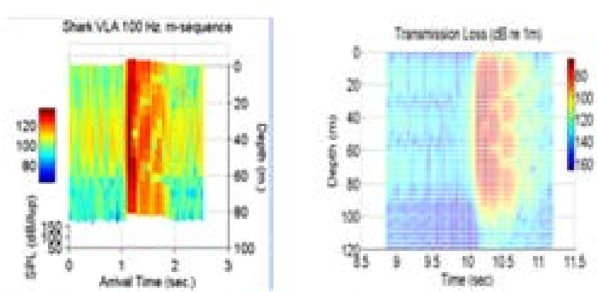

Fig.1. Measured and computed modes (100 Hz)

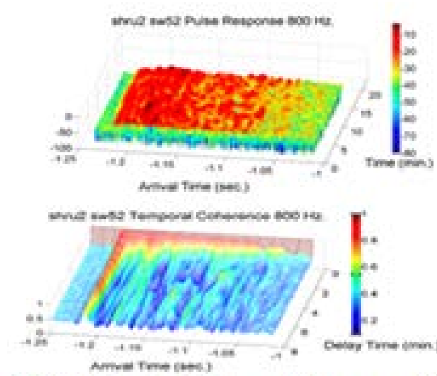

Fig.2. Pulse Arrivals and Coherence (800 Hz.)

For low frequencies, <100 Hz, the bottom appears flat and under low internal wave activity perfect modes are formed (Fig 1). Coherence times of hours are observed - essentially unlimited coherent times for all modes. As internal wave energy along the propagation path increases the coherence times decrease to a few minutes for all modes.

For high frequencies, >800 Hz. only the single lowest order mode is observed with coherence times of minutes even under very low internal wave energy (Fig.2). Higher order modes are smeared in space and time and have coherence time of less than a few seconds.

For the intermediate frequencies all modes are recognizable but higher modes are deformed and smeared so that higher order modes are less temporally coherent than lower order modes. Fig. 3.

It became apparent early on in the analysis that we could not account for the observations by sound speed variability and internal waves alone. It was necessary to introduce boundary variability.

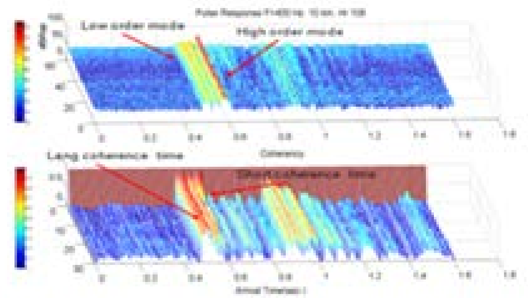

Fig.3. Pulse Arrivals and Coherence (400 Hz.)

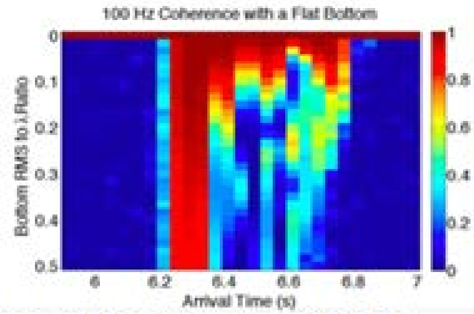

Fig. 4. Mode Coherence (100 Hz.)

We model effects of small changes in bathymetry along the path of propagation shown in (Fig.4) as a ratio to acoustic wavelength. All modes except the first become randomized (lose recognizable shape) when compared to ideal (flat bottom modes)
All it takes to distort higher order modes is an RMS of .1x acoustic wavelength. Small scale RMS fluctuations that could cause scattering are not allowed, only scale length longer than the Fresnel zone of a bottom interaction.

The model results consistently explain the observations. The 0^{th} order mode travels directly down the channel with minimum bottom interaction. Sound speed fluctuations may distort the modes but not the bottom. Higher order modes are randomized by multiple bottom interaction. It does not take much - only 1/2 wavelength. The bottom appears flat to the lowest frequencies. The observed mode distortions accounts for the loss of long term phase coherence. Linear motion or sound speed perturbation produces a random phase shift. Gain from phase coherent processing is lost.